International Journal of Mechanical and Production Engineering Research and Development (IJMPERD)
ISSN(P): 2249-6890; ISSN(E): 2249-8001
Vol. 9, Issue 1, Feb 2019, 575-584

THE DEVELOPMENT OF HYBRID ALUMINIUM-DIAMOND-HEXAGONAL BORON NITRIDE METAL MATRIX COMPOSITES FOR HEAT SINK APPLICATIONS

K. V. P. CHAKRADHAR[1], V. ANIL KUMAR[2] & KOTARI SAIRAM[3]

[1,3]Faculty, Department of Mechanical Engineering, Vardhaman College of Engineering, Shamshabad, Hyderabad, India

[2]Research Scholar, Department of Mechanical Engineering, SVNIT, Surat, Gujarat, India

ABSTRACT

Modern material researchers are focused on developing new metal matrix composite (MMCs) which have superior strength-to-weight ratio, thermal and electrical properties. Compared to monolithic metals, metal matrix composites have better mechanical, thermal and electrical properties. There is enormous demand for materials which have high thermal conductivity, smaller size and low coefficient of thermal expansion that can be used as a heat sink in electronic devices, primarily for computer processors, semiconductor lasers, and high-power microchips. In this research work an effort has been made to prepare hybrid aluminium metal matrix composite and to study its thermal properties and microstructure. Preparation of hybrid aluminium metal matrix composite by a powder metallurgy process was made by reinforcing synthetic diamond and hexagonal boron nitride (HBN). Aluminium powder was used because of its low density and reasonably high thermal conductivity, diamond for its very high thermal conductivity and HBN was used because of its better thermal conductivity and wettability properties. The objective of this work is to analyse the suitability of the composite material for heat sink applications.

KEYWORDS: Hybrid, Metal Matrix Composite, Aluminium, Diamond, Hbn, Powder Metallurgy, Microstructure & Thermal Conductivity

Received: Oct 19, 2018; **Accepted:** Nov 09, 2018; **Published:** Jan 28, 2019; **Paper Id.:** IJMPERDFEB201955

INTRODUCTION

A variety of new advanced composite materials are now available that provide great advantages over conventional materials for electronic packaging, thermal control, including extremely high thermal conductivities (more than twice that of copper); low tolerable coefficients of thermal expansion; weight savings up to 80 percent; extremely high strength and stiffness; low-cost, net-shape fabrication processes; and cost reductions as high as 65 percent. [1,2,3]. In particular, very high thermal conductivities have been achieved using diamond powder-based metal matrix composites (MMC) with aluminium as a matrix material [4]. However, in the case of copper and silver and for production routes not including the sintering of diamonds, the adjunction of an element (e.g. B, Cr in Cu and Si in Ag) to the matrix metal are necessary to obtain the desired properties. Moreover, the obtained properties vary strongly as a function of the diamond particle size [5]. In the cases of aluminium/diamond [6] and Cu (Cr) /diamond [7,8], the formation of isolated carbides or a carbide layer, respectively, at the interface between the matrix and the diamond had been observed and was suggested to be responsible for good thermal coupling between the matrix and the particles. For Cu-based diamond composites, the absence of such a coupling layer

leads, typically, to very poor adhesion. The heat sink is a passive heat exchanger that transfers the heat generated by an electronic or a mechanical device in a coolant fluid in motion. Then the transferred heat leaves the device with the fluid in motion, therefore allowing the regulation of the device temperature at physically feasible levels. In computers, heat sinks are used to cool central processing units or graphics processors. Heat sinks are used with high-power semiconductor devices such as power transistors and optoelectronics such as lasers and light emitting diodes (LEDs), where the heat dissipation ability of the basic device is insufficient to moderate its temperature. The main requirements of the electronics industry for heat sinks, electronic chips are high thermal conductivity and smaller size. A major problem challenging specialists of materials sciences in present-day is the development of compact, cheap to fabricate heat sinks for electronic devices, primarily for computer processors, semiconductor lasers, high-power microchips, and electronics components. The materials currently used for heat sinks of such devices are aluminium and copper with thermal conductivities of about 250 W/ m.K and 400 W/ m.K respectively [9,10]. Scientists are continuously trying to improve various properties of engineering materials. This led to the new category of materials called composite materials; they are composed of a combination of distinctly different two or more micro or macro constituents that differ in the form of composition and it is insoluble in each other. Composite materials have a continuous, phase called the matrix; and a dispersed, non-continuous, phase called the reinforcement. The reinforcing phase material may be in the form of fibers, particles, or flakes. The matrix phase materials are generally continuous. In a composite, each material retains its original properties, but when composite it yields superior properties which cannot be obtained separately [11].

The present work analyses the thermal conductivity and microstructure of aluminium/ diamond/ hexagonal boron nitride combination and its suitability for heat sink application.

EXPERIMENTAL WORK

Material and Methods

The composites were prepared using aluminium, synthetic diamond and hexagonal boron nitride materials. Due to its relatively low density and better thermal conductivity property, Aluminium 6063 material was used here as one of the material for heat sink. The composition and properties of Aluminium 6063 are presented in the Tables 1 and 2. The powder was purchased from M/s Special Steel, Mumbai.

Table 1: Chemical Composition of Aluminium 6063 (at%).

Al	Si	Fe	Cu	Mn	Mg	Zn	Ni	Cr	Ti
0.975	0.25	0.212	0.002	0.015	0.458	0.002	0.008	0.05	0.012

Table 2: Properties of Aluminium 6063

Properties	Density	Coefficient of Thermal Expansion	Thermal Conductivity	Heat Capacity
Value	2.69 kg/m^3	2.34 x 10^{-5} K^{-1}	200 W/mK	0.9 J/g^{o}C

Figure 1: Aluminium 6063 Powder

Synthetic diamond of MBD grade in powder form was used as the reinforcement material. The diamond particles were procured from M/s Vivek agencies, Mumbai. Diamond an allotrope of carbon possess high thermal conductivity up to 1500 W/m.K and coefficient of thermal expansion of 1 – 2 x 10^{-6} m / m°C. It occupies a prominent place among the materials which offer promise for developing high-efficiency heat sinks for semiconductor lasers, high-frequency, and high power transistors, optical amplifiers, power LEDs, integrated circuits. The properties of synthetic diamond are presented in Table 3. Due to its very high thermal conductivity, synthetic diamond was used here as one of the materials for heat sink.

Table 3: Properties of Diamond

Properties	Density g/cm^3	Coefficient of Thermal Expansion °C^{-1}	Thermal Conductivity W/m.K	Thermal Diffusivity cm^2/s	Heat Capacity J/(mol.K)	Electric Modulus GPa
Value	3.51	1 x 10^{-6}	1500	12.4	6.19	1050

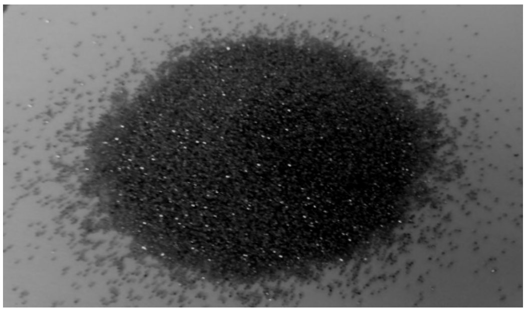


Figure 2: Synthetic Diamond Particles

The most stable crystalline form is the hexagonal one, also called h-BN, α-BN, g-BN, and graphite boron nitride. Hexagonal boron nitride has a layered structure similar to graphite. Within each layer, boron and nitrogen atoms are bound by strong covalent bonds, whereas the layers are held together by weak van-der Waals forces. Due to its better wet tability property and better thermal conductivity, HBN was used here as one of the materials for heat sink. The properties of hexagonal boron nitride are presented in Table 4.

Table 4: Properties of HBN

Material Property	Volume
Thermal conductivity	1700 w/mk
Density	2.3 g/cm^3
Thermal expansion coefficient	1x10^{-6} °C^{-1}
Particle size	5 microns

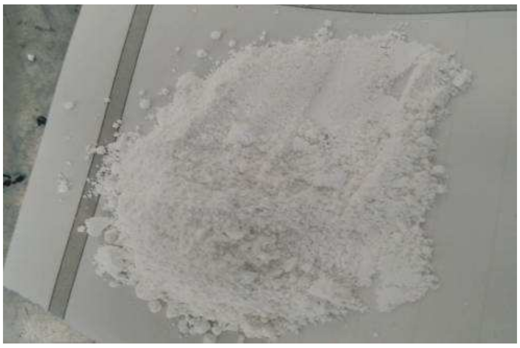


Figure 3: Hexagonal Boron Nitride Powder

Blending of Powders

Blending is the combination of powders to produce a homogeneous mixture. The required quantity of the combination of powders was taken into a bowl and mixed manually for nearly 10 minutes.

EQUIPMENT USED

Die and Punch Set

The die and punch set as shown in Figure 3 is the equipment in which the blended powders are poured. The die has the diameter and height required for the specimen, and the punch applies the required pressure on the powders.

Figure 3: Die and Punch Set

Compaction Process

The die and punch along with the blended powders is placed in between the hydraulic jack that is shown in Figure 4. In this process nearly 2000 MP of pressure of the load is applied to the die and punch. Due to the uniform load applied by the jack on the punch, the blended powders in the die and punch are compacted into a solid specimen. The same process is followed for all the four specimens. The capacity of the jack is 100 tons.

Figure 4: Hydraulic Jack

Thermal Conductivity

The thermal conductivity of the sintered specimens was measured using thermal conductivity measuring apparatus built in-house. The measurement was done based on parallel conductance technique. The test was conducted as per ASTM E1530.

The following equation was used for calculation of thermal conductivity:

$$Q = \frac{KA(t_1 - t_2)}{x} \quad (1)$$

$$R = \frac{(t_1 - t_2)}{q} \quad (2)$$

$$K = \frac{x}{R} \quad (3)$$

Where Q is the heat flux (W), K is the thermal conductivity (W/m-K), A is the cross- sectional area (m^2), t_1-t_2 is the difference in temperature (K) and x is the thickness of the sample, R is the resistance of the sample between hot and cold surfaces (m^2-K/W).

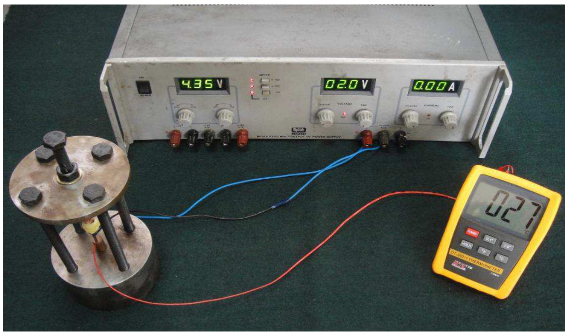


Figure 5: Thermal Conductivity Measurement, Experimental Setup

Composite Preparation

The required hybrid composite was prepared by blending the powders of Aluminium, Synthetic diamond and Hexagonal boron nitride. Four specimens of varying compositions of Aluminium, Synthetic diamond and Hexagonal Boron Nitride were prepared. Table 5 presents the different compositions of the specimens.

The powders were taken in required weight percentages (wt.%) in a bowl and the combination of powders was blended to produce a homogeneous mixture. Blending was the combination of powders to produce homogeneous mixture.

The powder combination was mixed manually for approximately 10 minutes, till a homogenous mixture of hybrid composite was obtained.

Table 5: Composition in wt.% of the Specimen

Specimen No.	Aluminium (wt%)	Diamond (wt%)	HBN (wt%)
1	65	30	5
2	60	35	5
3	55	40	5
4	45	50	5

The blended mixture was then compacted using a die and punch arrangement. Specimen of 50 mm height and 20 mm diameter was prepared. The die and punch setup along with the blended mixture was placed in a hydraulic jack of 100 tons capacity. About 2000 MPa pressure was applied on the blended mixture and this produces a solid composite specimen. The same process was followed for all the four specimens and graphite was used to make the die surface clean and smooth.

The compacted specimen was then sintered in a furnace to a temperature of about 600^{o}C, under protected environment. Sintering was done to improve the bonding between the particles of the composite. After sintering was completed, the composite was cut into the required standard dimensions.

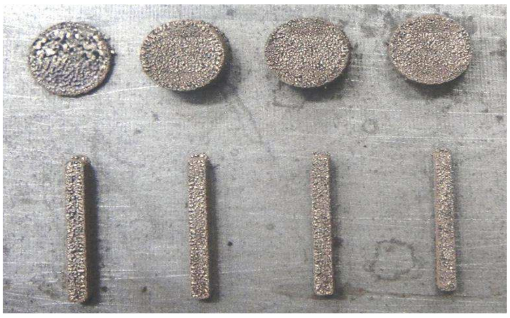


Figure 6: Specimens after Cutting

RESULTS AND DISCUSSIONS

The effect of reinforcement of aluminium with diamond and hexagonal boron nitride (HBN) on the thermal conductivity property of the metal matrix composite was studied. It was observed that an increase in diamond content enhanced the thermal conductivity.

Density

Archimedes' principle was used to measure the density of laser-sintered samples. Weight of samples was first measured in air, then in water. The density values calculated can be observed as shown in Table 6.

Table 6: Density of Specimens

Composition (Al+Diamond+HBN)	Weight in air (g)	Weight in water (g)	Volume Displaced (cm^3)	Density (g/cm^3)
Specimen 1	2.75	2.39	0.36	7.63
Specimen 2	2.65	2.31	0.34	7.79
Specimen 3	2.55	2.23	0.32	7.96
Specimen 4	2.45	2.21	0.24	10.20

Thermal Conductivity

The measurements of thermal conductivity were done to all the specimens. Here 30 wt% of diamond combined with 65 wt% of aluminium and 5 wt% of HBN gave a thermal conductivity of 428 W/mK, the least while 50 wt% of diamond combined with 45 wt% of aluminium and 5 wt% of Hbn gave a thermal conductivity of 586 W/mK, the maximum. It is observed that the thermal conductivity is directly proportional to density. HBN powder with artificial diamond has enhanced the wettability and helped in achieving good interfacial bonding between the diamond and aluminium. This good interracial bonding helped in resulting in effective heat transfer. Increase in wt.% of diamond helped in increase in the effective heat transfer leading to an increase in thermal conductivity. Table 7 presents the thermal conductivity values of the composite specimens.

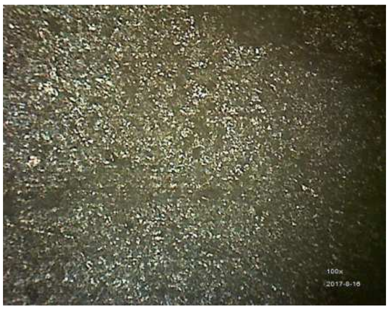
Table 7: Thermal Conductivity of the Specimens

Material Composition (Al+Diamond+HBN)	Thermal conductivity (W/mK)
Specimen 1	428
Specimen 2	462
Specimen 3	528
Specimen 4	586

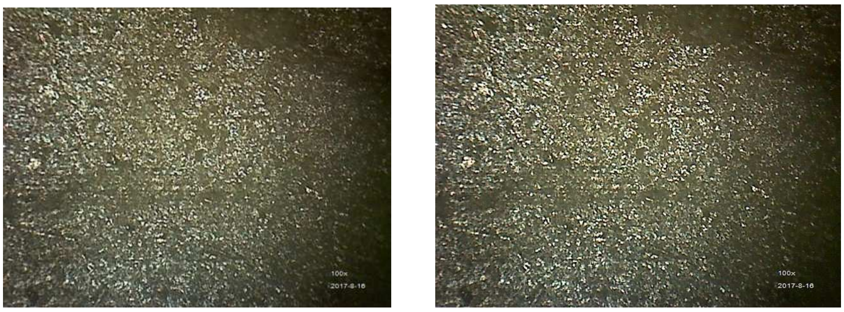
Microstructure Studies

The specimens were prepared to carry out the micro-structural study. One specimen for each composition was selected to investigate the microstructure by optical microscopy at 100X magnification. The microstructure of the specimen was studied by taking central part of the composition block. The figures 7(a-d) show the optical micrographs of MMC for different weight percentages by keeping HBN wt.% constant. The wt.%'s of Aluminium and Diamond were varied. A good interfacial bonding between aluminium and diamond was observed from the microstructure studies of the composites, and this could be due to the presence of HBN, that has good wettability property. Increase in diamond wt.% that has a better thermal conductivity property and presence of HBN gave better bonding and higher thermal conductivity. This was the reason that specimen 4 with higher diamond content exhibited higher thermal conductivity.

(a) Microstructure of Specimen 1



(b) Microstructure of Specimen 2



(c) Microstructure of Specimen 3 **(d) Microstructure of Specimen 4**

Figure 7: Microstructure Studies of the Specimens

CONCLUSIONS

The following are the conclusions derived from the present work that was carried out:

- The sintered parts were characterized for density, microstructure and thermal conductivity studies.
- Density of sintered parts was observed to be higher where the diamond wt% was high. It was found that there was an increase in thermal conductivity with an increase in density.
- A good interfacial bonding between aluminium and diamond was observed from the microstructure studies of the composites, and this could be due to the presence of HBN [11-13]. Increase in diamond wt.% and presence of HBN gave better bonding and higher thermal conductivity. This was the reason that specimen 4 with higher diamond content exhibited higher thermal conductivity.
- Thermal characterization of sintered aluminium and diamond (with mixing of HBN) specimens was carried out using Thermal Conductivity Measuring Apparatus developed in-house. It was observed that there was an increase in thermal conductivity with an increase in wt.% of diamond.
- A higher thermal conductivity of 586 W/m.K was achieved at a density of 10.2 g/cm3 and wt.% of diamond at 50 wt.%, indicating that the developed material is suitable for heat sink applications.

ANTI-PLAGIARISM DECLARATION

I have read and understood the rules on plagiarism. I hereby declare that this piece of written work is the result of my own independent scholarly work, and that in all cases material from the work of others is acknowledged, and quotations and paraphrases are clearly indicated. No material other than that listed has been used. This written work has not previously yet been published.

REFERENCES

1. *Zweben C. (2007), "Advances in high-performance thermal management materials—a review", Journal of Advanced Materials, 39, (pp-3–10).*
2. *Zweben C. (2005), "Advanced electronic packaging materials", Advanced Materials and Processes, 163, (pp-33–37).*
3. *Zweben C. (1998), "Advances in composite materials for thermal management in electronic packaging", Journal of Management, 50, (pp- 47–51).*

4. Molina J.M., Rhême M., Carron J., Weber L. (2008), "Thermal conductivity of aluminum matrix composites reinforced with mixtures of diamond and SiC particles", Scripta Materialia, 58, (pp- 393–396).
5. Tavangar R., Molina J.M., Weber L. (2007), "Assessing predictive schemes for thermal conductivity against diamond-reinforced silver matrix composites at intermediate phase contrast", Scripta Materialia, 56, (pp-357–360).
6. Beffort O., Khalid F.A.,, Weber L. (2006), "Interface formation in infiltrated Al(Si)/diamond composites", Diamond and Related Materials, 15, (pp- 1250–1260).
7. Nagaral, M., Auradi, V., & Ravishankar, M. K. (2013). Mechanical behaviour of aluminium 6061 alloy reinforced with al2o3 & graphite particulate hybrid metal matrix composites. International Journal of Research in Engineering & Technology (IJRET) Vol, 1, 193-198.
8. Schubert T., Ciupinski L., Zielinski W. (2008a), "Interfacial characterization of Cu/diamond composites prepared by powder metallurgy for heat sink applications", Scripta Materialia, 58, (pp- 263–266).
9. Schubert T., Trinidade B., Weisgarber T. (2008b), "Interfacial design of Cu-based composites prepared by powder metallurgy for heat sink applications", Material Science and Engineering A, 475, (pp-39–44).
10. Zhanqiu Tan., Ding-Bang Xiong., Genlian Fan., Zhang D. (2018), "Enhanced thermal conductivity of diamond/aluminum composites with tungsten interface nanolayer", Materials and Design, 47, (pp-160-166).
11. Sijoa M.T., Jayadevan K.R. (2016), "Analysis of Stir Cast Aluminium Silicon Carbide Metal Matrix Composite: A Comprehensive Review", Procedia Technology, 24, (pp-379-385).
12. Rushikesh Khatavkar A., Abhijeet Mandave K., Devakant Baviskar D., Samir Shinde L. (2018), "Influence of Hexagonal Boron Nitride on Tribological Properties of AA2024-hBN Metal Matrix Composite", International Research Journal of Engineering and Technology, 05, (pp-3792-3798).
13. Reddy, A. C. Effects Of Adhesive and Interphase Behavior Of Aa6061/Aln Nanoparticulate Metal Matrix Composites.
14. Yathiraj K., Chandraiah M.T., Mohan Kumar A.R. (2016), "Evaluation of Mechanical Properties of Aluminium 6061 Reinforced with Boron Nitride MMC's using Optical Microscope", International Journal of Innovative Research in Science, Engineering and Technology, 5, (pp-16128-16133).
15. Pranith Shetty., Srinivas N., Sudesh Bhat., Trupthesh Shetty, Mithun. B. R. (2018), "Microstructure and Mechanical Properties of Al2024-B4C-hBN Reinforced Metal Matrix Composites", International Journal for Research in Applied Science & Engineering Technology, 6, (pp-364-368).